AD-A133 473 DIELECTRIC LOSS MEASUREMENT AT MILLIMETRE WAVE FREQUENCIES USING AN UNTUN..(U) ROYAL SIGNALS AND RADAR ESTABLISHMENT MALVERN (ENGLAND) D J GUNTON JUN 83 1/1

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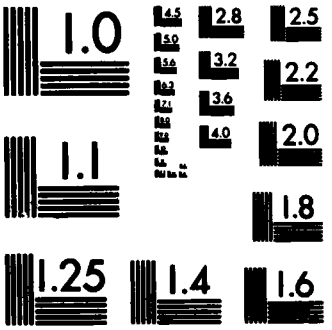

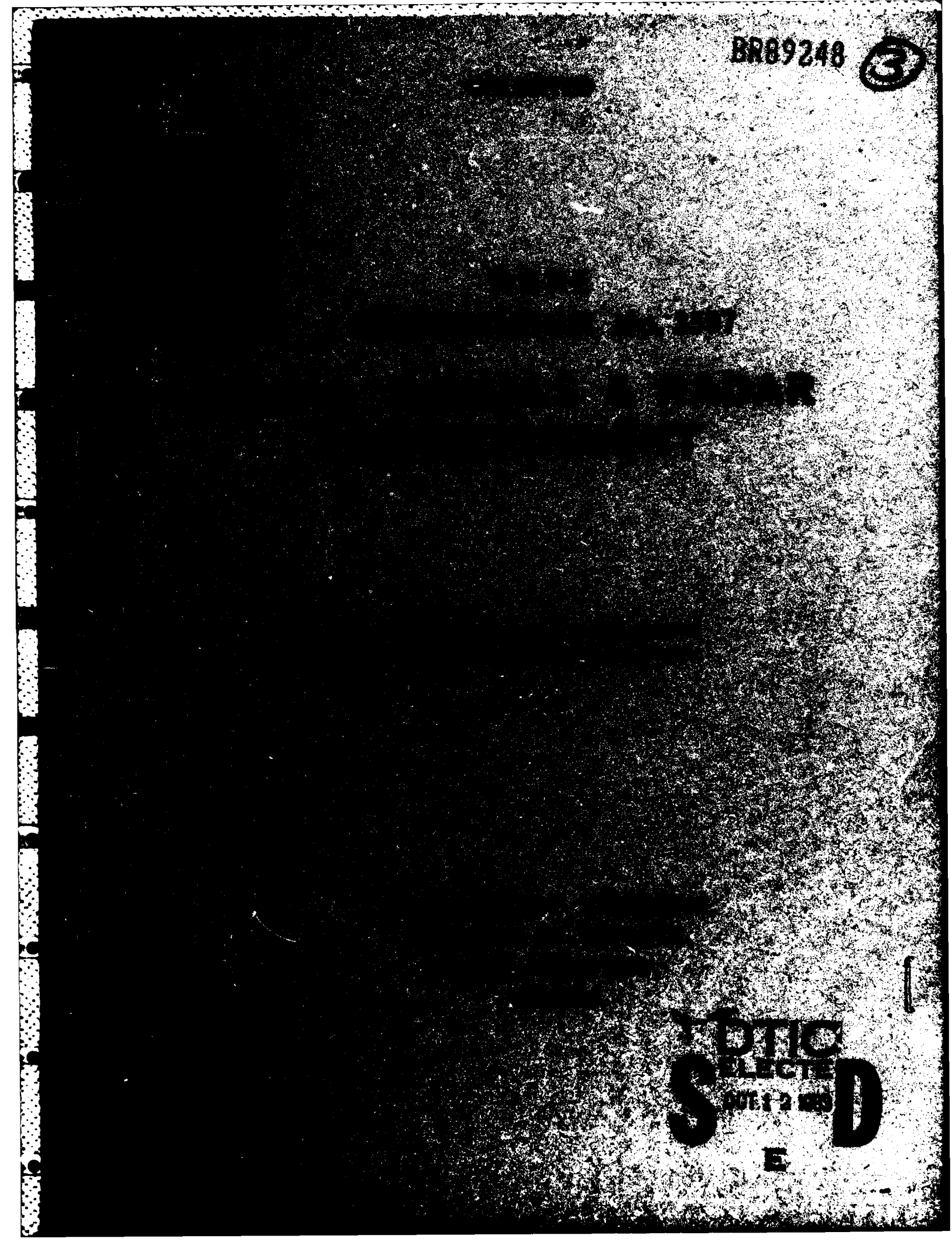

ROYAL SIGNALS AND RADAR ESTABLISHMENT

Memorandum 3597

TITLE: DIELECTRIC LOSS MEASUREMENT AT MILLIMETRE WAVE FREQUENCIES USING AN UNTUNED CAVITY

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DATE: June 1983

SUMMARY

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DIELECTRIC LOSS MEASUREMENT AT MILLIMETRE WAVE FREQUENCIES USING AN UNTUNED CAVITY

D J Gunton

1 INTRODUCTION

The assessment of dielectric materials for use in resonators, lenses or dielectric waveguides at millimetre wave frequencies requires a knowledge of the permittivity and the dielectric loss. For many materials the permittivity is known because of measurements made at lower frequencies (eg X-band) and it is only weakly dependent on frequency, at least for the amorphous ceramics and organic polymers which are of interest in lens applications. However, the absorption coefficient can vary strongly with frequency so that an X-band measurement is not a good measure of the loss at millimetre wavelengths, and a further determination of the absorption must be made. At frequencies around 100 GHz conventional resonant cavity methods become difficult because of the small size of such cavities and the need accurately to shape a small sample. Transmission methods using quasi-optical techniques, such as Fourier Transform Spectroscopy, are possible and can give highly accurate values of both the real and imaginary parts of the propagation constant. Unfortunately, they require elaborate and expensive equipment and need samples which are adequately flat and parallel. For the present work it is sufficient only to know the loss tangent ($\tan \delta$) to within a factor of two and an advantage to have a method of measurement which is sample-shape independent. The untuned, or overmoded, cavity method of measurement is sufficient on both these counts (although accuracy better than a factor of two is possible by an extended set of measurements on a given material). Further, the basic equipment need not be expensive and the measurements are relatively quick compared with the spectroscopy method.

An account is given here of the basis of the untuned cavity method and the information which it yields, together with notes relating to the special case of high permittivity samples. Finally, the experimental hardware and its operation is described. A fuller description of the basic method has been given by Llewellyn-Jones et al*.

2 THEORETICAL BASIS

An untuned cavity is a large volume contained by conducting walls. A typical dimension (the cavity is preferably not regular in shape) is many wavelengths so that the cavity will support a large number of modes. The greater the number of modes excited by the incoming radiation the more spatially uniform is the energy density within the cavity, and hence the less critically dependent on sample position is the total power absorbed by the sample. Further, the larger the sample so that it supports in itself a large number of modes the less dependent is the cavity response on sample shape.

The measurement consists of finding the change in Q of the cavity from

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* Llewellyn-Jones D T, Knight R J, Moffat P H and Gebbie H A; IEE Proc. 127 A, 8, pp 535-540, 1980.

its empty, unloaded value Q_o to a new value Q_L when a sample is introduced. If the Q of the sample is Q_s then

$$\frac{1}{Q_L} = \frac{1}{Q_o} + \frac{1}{Q_s} . \qquad (1)$$

A calibration procedure consists of applying a calculable loading to the cavity Q_h by opening a circular hole in the cavity wall. Then the unloaded Q_o is given by

$$Q_o = Q_h \left(\frac{Q_o}{Q_L} - 1 \right) . \qquad (2)$$

Provided that the area of the circular hole is small compared with the total surface area of the cavity walls, and provided that it is of sufficient diameter for diffraction effects to be negligible, the energy lost through it results in an equivalent Q_h given by

$$Q_h = \frac{4V\omega}{Ac} , \qquad (3)$$

where V is the cavity volume, ω the angular frequency, A is the area of the aperture and c is the velocity of light. Hence, knowing Q_o, the value of Q_s can be obtained from eq (1) after a measurement of Q_L. It only remains to establish a method of measuring Q_L.

To do this we observe from the definition of the Q factor:

$$Q = \frac{\omega \text{x stored energy}}{\text{rate of energy loss}} = \frac{\omega U}{L} \qquad (4)$$

the value of U at equilibrium is proportional to Q. Ordinarily, a determination of the total stored energy would need an integration over the whole volume, but in the multi-mode limit the energy density is uniform so that a measurement of power at on position only is needed to obtain U, and hence a measure of Q. For convenience the power measuring position is close to a wall of the cavity, and a power detector is positioned adjacent to a small hole in the cavity wall. In more sophisticated experiments some form of spatially adjustable power detector (for example, a small horn attached to a length of waveguide) can be employed to monitor the power levels at a range of positions within the cavity and to avoid making a measurement close to the cavity wall, but the external detector near to a small hole is quite adequate for basic dielectric assessment.

The assumptions implicit in the replacement of a Q measurement by a single local power measurement are discussed by Lamb*, but they concern the distribution of energy among the various modes. If a guide to the field uniformity is taken as the number of modes supported by the cavity, then the following expressions are instructive.

(i) CW Radiation Applied to the Cavity

Let the cavity volume be V, the wavelength λ and the Q-factor Q_o, then the number of modes n_1 is given by

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* Lamb W E, Phys Rev 70, pp 308-17, 1946.

$$n_1 = 2 \times \frac{4\pi V}{\lambda^3 Q_o} . \qquad (5)$$

This follows from the number of points in k-space in a shell of radius $k = 2\pi/\lambda$ and thickness Δk, where Δk relates to the frequency width of the cavity resonance. The pre-multiplying factor of 2 takes into account the two polarisation components of a propagating wave in the cavity. For a cavity of the type we have used experimentally, $V = 4.5 \times 10^4$ cc, $Q_o \simeq 10^5$ so with $\lambda = 0.3$ cm, $n_1 \simeq 420$.

(ii) An RF Pulse of Duration Δt, Centre Frequency f

When Δt is less than the ring time of the cavity ($2Q/f$), Q_o is replaced by $f\Delta t/2$ and the effective number of modes is*

$$n_2 = 2 \times \frac{8\pi V}{\lambda^3 f \Delta t} . \qquad (6)$$

(iii) Swept CW, Slow Detector

The use of a slow power detector enables the effective number of modes to be increased significantly by a swept frequency input. The 'instantaneous' number of modes is not changed, but the larger number of modes through which the cavity and sample are taken during the sweep is the total number whose effect is averaged by the detector. So, for a sweep time short compared with the detector time constant, the number of modes is, from eq 5,

$$n_3 = 2 \times \frac{8\pi V}{\lambda^3} \cdot \frac{\Delta f}{f} , \qquad (7)$$

for a sweep width Δf. For our case, when $\lambda = 0.3$ cm, $n_3 \simeq 10^8 \Delta f/f$. A sweep of 4% was used in the experimental work, giving some 4×10^6 modes, or an increase by a factor of 10^4 compared with CW operation.

Field Uniformity

It is found in practice that with CW radiation the use of a mechanically rotated metal paddle in the cavity serves to increase the number of modes existing over the integration time of the detector to give a field uniformity of approximately 3 or 4%. (This was determined by moving a small lossy probe around within the cavity and noting the measured output power variation). When the paddle did not rotate the uniformity was found to be much worse, and variations of over 100% were observed. The use of swept CW radiation resulted in a uniformity of output power with probe position of better than 0.5%, and was limited by room pressure noise in the Golay detector. Whether the paddle was rotating or not made very little difference to the uniformity, as would be expected. The variation had a radial periodicity which was observed during the characterisation of the cavity, but this was removed when the axis of the paddle was rotated by about 20° so that it was no longer collinear with the axis of cylindrical symmetry of the cavity.

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* Lamb W E, loc. cit.

3 INTERPRETATION OF THE MEASUREMENTS

A measurement consists of determining the output power from the empty cavity P_o, together with the output power from the loaded cavity P_L. The ratio $(P_o-P_L)/P_L = r$ is of interest; we show how for a low loss dielectric the loss tangent is related to r and how a measure of r may be used to estimate the reliability of the method for a sample of a given size, shape and permittivity.

Consider a dielectric of complex permittivity $\varepsilon_1 + j\varepsilon_2$, or complex refractive index n + jk. The loss tangent is given by

$$\tan\delta = \varepsilon_2/\varepsilon_1;$$

the power absorption coefficient α is given by

$$\alpha = 2\omega k/c.$$

Hence

$$\tan\delta = \frac{2nk}{n^2-k^2} \quad (\text{since } (n+jk)^2 = \varepsilon_1+j\varepsilon_2)$$

$$= \frac{n\alpha c}{\omega(n^2-k^2)} \quad .$$

When $n >> k$

$$\tan\delta = \frac{\alpha c}{\omega n} \quad . \tag{8}$$

For isotropic radiation the absorption coefficient α is related to the absorption cross-section σ_o by*

$$\sigma_o = 4v\alpha, \tag{9}$$

where v is the sample volume.

The measurement of Q_s for the sample can be related to an effective cross-section through eq 3, so that an expression for $\tan\delta$ becomes

$$\tan\delta = \frac{V}{vnQ_s}$$

$$= \frac{1}{\theta}\,\frac{V}{Q_o}\,\frac{r}{vn} \quad . \tag{10}$$

A parameter θ has been introduced; this is because a more detailed analysis shows that when the sample is not sufficiently large and irregular for it to be an overmoded cavity in its own right (or, alternatively, when the incoming radiation is not sufficiently incoherent), there is a shape factor (denoted here by θ) which modifies the absorption cross-section σ_o. Llewellyn-Jones et al* have calculated θ for a range of values of n and for a range of shapes. They find it to be approximately 1.6 for n greater than about 2, with very little variation between cubes, prisms and discs. For a powder $\theta = 1$.

The analysis so far has assumed low loss in the sample, and we now consider a method to check that a given measurement results in a valid

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* See, for example, Llewellyn-Jones, et al., loc. cit.

determination of tanδ. The problem which can arise is that if the sample is sufficiently lossy for the inner regions to be screened from the cavity electric field by the outer regions then measurements of r are not proportional to sample volume, as required by eq 10. Thus a graph of r against volume can be used to show up any inconsistency. Another check, which only requires one measurement, is to compare the apparent absorption cross-section σ_o, as determined by a measurement of r, with the geometrical surface area. The resulting ratio is the 'fractional blackness' of the sample. This should preferably be below 0.1. The absorption cross-section is given by, from eqs 8, 9 and 10

$$\sigma_o = \frac{4V}{Q_o} \frac{2\pi}{\lambda} r. \tag{11}$$

(In the cavity used experimentally, $V = 4.5 \times 10^4$ and $Q_o = 9 \times 10^4$, so that $4V/Q_o$ had a numerical value of 2).

Evaluation of the fractional blackness is affected by the permittivity of the sample, as follows. Consider a dielectric sample which is 100% black. That is, all radiation which passes into it is absorbed. However, the proportion entering is related to that incident upon it by the refractive index, so that a correction must be applied to the geometrical surface area A_g to find the maximum absorption area A_a, defined as the value of σ_o for a completely absorbing sample.

$$A_a = \frac{4n}{(1+n)^2} A_g \tag{12}$$

The fractional blackness is then σ_o/A_a. In the case of a high permittivity material the correction can be quite significant: for strontium titanate, for which $n = 14$, $A_a = 0.25A_g$. In practice, if the fractional blackness is high for a sample then a reduction in its volume can reduce the fraction; a series of measurements can be made and an extrapolation used to obtain a better estimate for tanδ.

4 EXPERIMENTAL SYSTEM

A diagram of a cross-section of the cavity used is shown in fig 1 and a block diagram of the peripheral equipment in fig 2. The lid of the cavity had provision for opening up to three ports either to introduce a sample (usually contained in a polythene bag) or to replace one of the solid sealing discs by another disc in which was a circular hole of known size for calibration purposes. The input signal was switched at about 11 Hz with a pin diode in a waveguide. This served as a reference for the two-channel lock-in voltmeter which measured the output signal from a Golay power detector. The provision of an attenuator enabled checks on linearity to be performed. For the measurement of very small changes in power at the output of the cavity an offset facility on the lock-in together with the use of a chart recorder to ease interpretation of the measured changes resulted in the ability to detect values of r as low as 0.002. Such small values were found for small volumes of very low loss materials such as PTFE or quartz, or when measurements were made of the absorption by semiconductor surfaces if an estimate of reflection coefficient (and hence conductivity) was required.

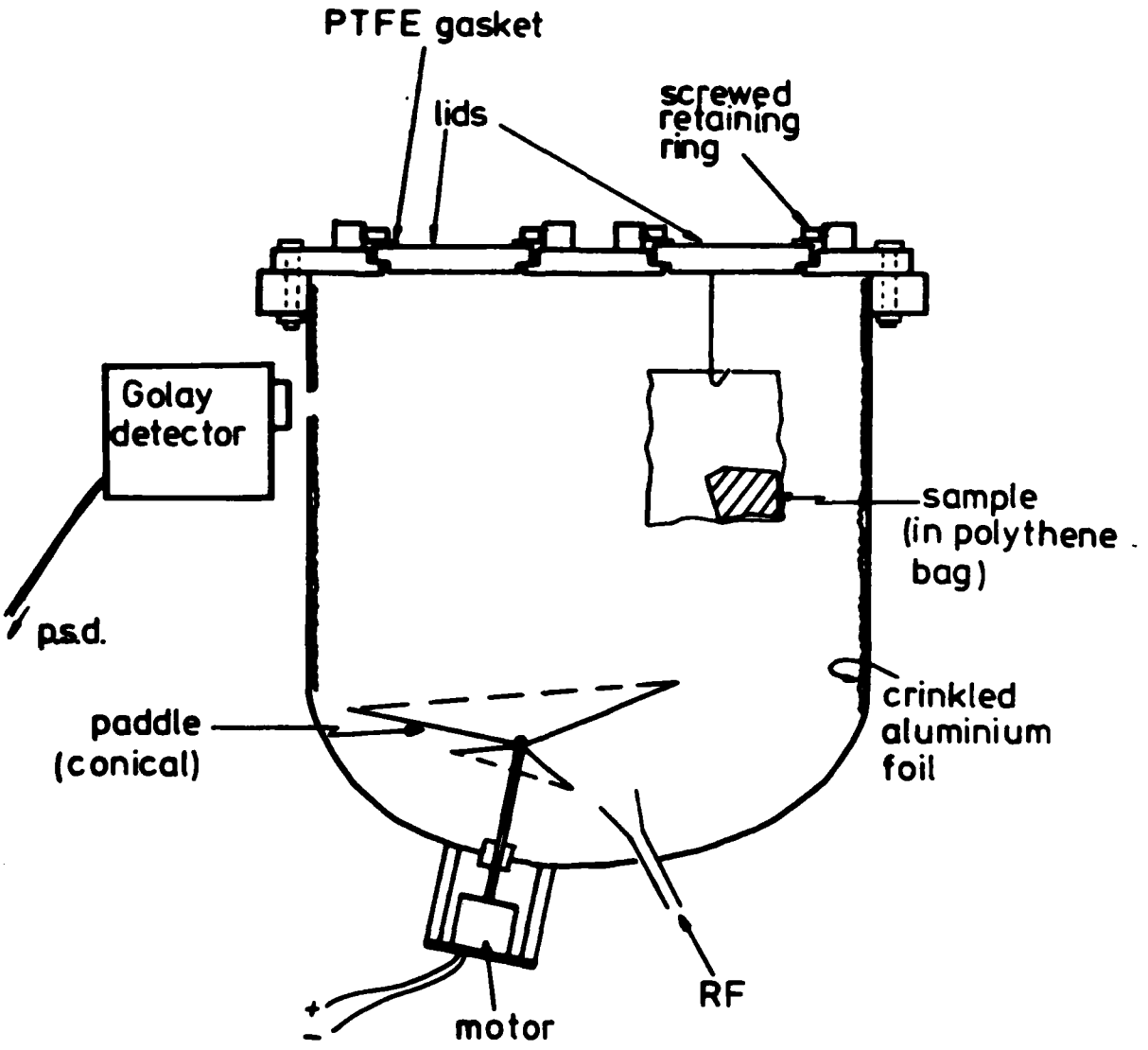

Figure 1 Cross-section of the Untuned Cavity

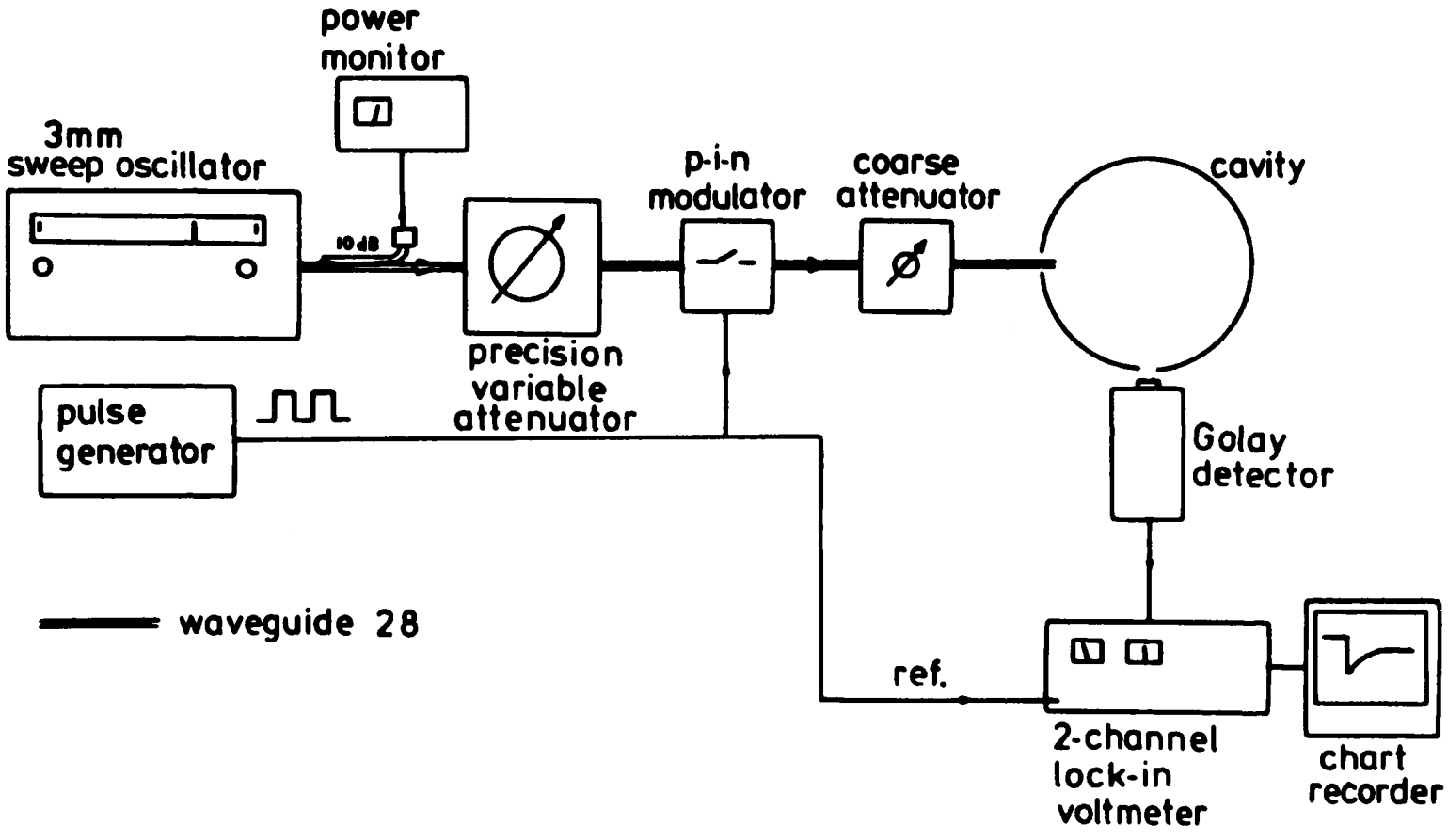

Figure 2 Block Diagram of the Untuned Cavity Measurement System

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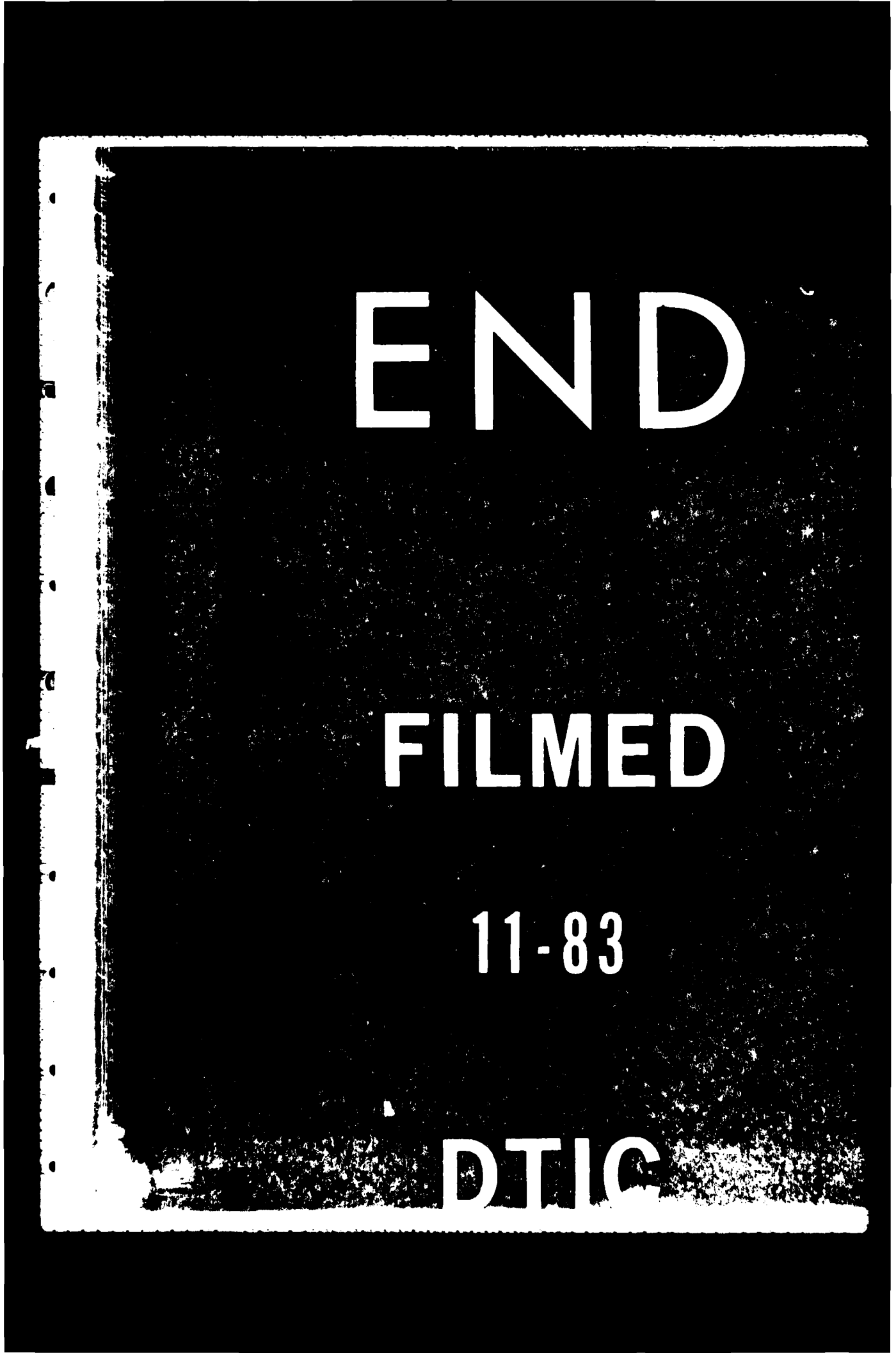
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